Discussion of "Comments on Effect of the Inclination of the Electric Field on the Inductive Charging Mechanism in Thunderclouds"

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In his recent comments, Saunders (1978) discusses the effects on charge transfer in the "inductive charging" process (Elster and Geitel, 1885 *et seq.*) caused by an inclination of the electric field and points out that the net charge transfer is proportional to the vertical component of the electric field vector **E**. He concludes that his results are independent of the field's horizontal components, of particle initial charge and of the position of the neutral zone, among other factors. While his conclusions about the importance of the field's vertical component and the cancellation of the averaged effects of the horizontal components in this process are correct,

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his communication conveys the impression that charge transfers by rebounding particles may be independent of their initial charges, and this, of course, is not correct.

The net charge transfer in each separating collision depends on the local electric field at the point where separation of the rebounding particles occurs. This field must be the vector sum of the induced polarization fields and those produced by the net charges on the particles. If the ambient electric field vector $\mathbf{E}_0$ in the absence of the particles is inclined at the angle φ_E relative to zenith, then the average magnitude of $\mathbf{E}$ over the lower surface of a spherical, conducting particle is $(3E_0 \cos\varphi_E)/2$.

Now, if the particle is a hailstone or raindrop of radius a and if it carries a net charge of q, then

$$\bar{E}_{\text{lower hemisphere}} = (\tfrac{3}{2})E_0 \cos\varphi_E - q/(4\pi\epsilon_0 a^2).$$

In this convention, the local direction of the average field is directed outwardly from the lower surface. The minus sign is chosen for the second term because $\bar{E}_{\text{lower hemisphere}}$ would have a downwardly directed component for positive q. When $\mathbf{E}$ is directed downwardly, $\varphi_E > \pi/2$ and $0 > \cos\varphi_E$; under these circumstances, the induction process would cause the drop to acquire a negative charge whenever uncharged (or negatively charged) cloud particles partially rebound from its lower surface. This aquisition of negative charge by separating particles could continue as long as $\bar{E}_{\text{lower hemisphere}}$ is negative and this condition will prevail as long as

$$q/(4\pi\epsilon_0 a^2) > (3E_0 \cos\varphi_E)/2.$$

Whenever

$$(3E_0 \cos\varphi_E)/2 > q/(4\pi\epsilon_0 a^2),$$

the average electric field over the surface of the lower hemisphere will be locally directed inwardly and, on the average, it will cause the *loss* of net drop charge in subsequent, charge-separating collisions. The critical maximum charge $q_{\max}$ at which charge separation by this process ceases is defined by

$$q_{\max} = 6\pi a^2 \epsilon_0 E_0 \cos\varphi_E.$$

This value for $q_{\max}$ is derived with the implicit assumption of a constant probability of particle rebound (and of the associated charge separation) from all portions of the lower hemisphere of the falling drop equally. Since both Whelpdale and List (1971) and Aufdermaur and Johnson (1972) have reported that the rebounding collisions of the type that can transfer charge occur most frequently at near-grazing incidence from near the drop equator, a strong angular dependence exists for the rebound probabilities. To obtain the appropriate average of the angular dependencies of the local field strength and of the probability of charge separating rebounds for induction-process calculations, the mean value theorem of the calculus must be used: The product of all the angular dependencies must be taken over each infinitesimal portion of the lower hemisphere and then integrated over the surface to obtain the combined effective value. The mean effective value for the product of the field strength and the rebound probability $p(\varphi)$ is given, in Sanders' notation, for the polar angle φ by

$$\overline{Ep} = \frac{6\pi a^2 E_0 \cos\varphi_E}{2\pi a^2} \int_0^{\pi/2} p(\varphi) \cos\varphi \sin\varphi d\varphi.$$

From examination of the data reported by Whelpdale and List and by Aufdermaur and Johnson, suggestions have been made that $p(\varphi)$ may be represented by $\sin^n\varphi_E$ [where n may be of the order of 100 or greater (Moore, 1975)]. If this is applicable, then

$$\overline{Ep} \approx 3E_0 \cos\varphi_E/(n+2),$$

and

$$q_{\max} \approx 12\pi a^2 \epsilon_0 E_0 \cos\varphi_E/(n+2).$$

From this relation, estimates can be made of the minimum values for the required E_0 that would produce the observed particle charges by the induction process:

$$|E_0| \geqslant \left|\frac{q_{\text{obs}}}{4\pi\epsilon_0 a_{\text{obs}}^2}\right| \left|\frac{n+2}{3\cos\varphi_E}\right|.$$

From a number of the observations reported for simultaneously measured precipitation sizes and charges (Rust and Moore, 1974; Gaskell *et al.*, 1977), values for the quantity $|q_{\max}/4\pi\epsilon_0 a^2|$ in excess of 10^6 V m^{-1} may be inferred for many particles. The minimum possible value of $|(n+2)/3\cos\varphi_E|$ is $\frac{2}{3}$ but its probable value is larger so that field strengths much greater than those available would seem to be required by the induction mechanism to produce some of the precipitation charges that have been reported.

The problems encountered by the induction mechanism may be even more difficult, for in our continuing balloonborne measurements of the charges carried downward by precipitation aloft, we find that the polarities of the precipitation charges are often the wrong ones to increase the local electric field strength. We typically find net negative charges falling from negatively charged regions of thunderclouds and net positive charges from positively charged regions. These observations suggest to us that the charges on precipitation aloft may often be the simple result of charge conservation as precipitation particles grow by the accretion of the masses and charges of the cloud particles through which they fall.

Accordingly, any numerical model of charge separation in thunderclouds that takes account of the net induction charge transfer between particles may require appreciable aid if the observed cloud electrification is to be modeled accurately. In conclusion it should again be pointed out that our present fund of knowledge about the conditions within thunderclouds is so meager that more and better measurements there (and in laboratories) are essential before we can draw any conclusions about the processes that operate in active clouds.

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